X-553-70-372

NASA TM X- 65441

GEOSTAR-II
A GEOPOTENTIAL AND STATION POSITION RECOVERY SYSTEM

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OCTOBER 1970

GSFC — GODDARD SPACE FLIGHT CENTER — GREENBELT, MARYLAND

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ABSTRACT

The GEOSTAR-II multiple arc geopotential coefficient and station position recovery system is described. This system was developed using the GEOSTAR-I system as documented in NASA X-533-69-544, as a base, and is the second in a series of geodetic programs under current development and use by the Mission and Trajectory Analysis Division.

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CONTENTS

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I. INTRODUCTION

The GEOSTAR-II system is a multiple arc, multiple satellite geopotential coefficient and station position recovery system. The basic features of this system are:

- The capability to form the normal equations for up to 250 geodetic and tracking model parameters per arc
- The capability to utilize a-priori information in the formation of a multiple arc least squares solution for up to 500 parameters
- The use of advanced numerical integration techniques
- The availability of a "stand-alone" orbit generator program which can be used to measure the performance of the integration process used for the equations of motion and variational equations.

The basic operational aspects, mathematical techniques and system design characteristics of the GEOSTAR-II system are based on the GEOSTAR-I system as documented in NASA X-553-69-544. In particular, all the current capabilities of the GEOSTAR-I system are available for use in the new system; however, because of additional core storage requirements of the II system, it is not recommended for use in lieu of the I system unless one or more of the new features are required, such as the extension to 250 parameters per arc.

The GEOSTAR-II system is written in 360 Fortran IV and is currently operational on the 360/95. The operating instructions are given in reference 4.

II. SYSTEM DESCRIPTION

The primary module of the GEOSTAR-II system is a modified version of GEOSTAR-I ODP program which has been extended to handle up to 250 model parameters per arc. Other modifications allow the use a-priori estimates and statistics in the multiple arc mode and the use of a more rapid integration starting process based on an iterative scheme using closed form Newtonian type formulas. Other system programs include MERGE, SOLVE, EIGENVALUE and ORBGEN.

The GEOSTAR-II system can be used to form the normal equations required to estimate up to 500 orbital and geodetic parameters using any number of tracking data arcs. This can be accomplished by first using the ODP program to form the normal equations on an arc by arc basis for up to 250 parameters per arc selected from the following·

- Geopotential coefficients through $C_{30,30}$ and $S_{30,30}$
- Tracking station coordinates
- State vector
- Drag and solar radiation constants.

These normal equations can be formed with or without the use of independent a-priori estimates and statistics. The resulting set of normal equations can then be combined to form a multiple arc solution for up to 500 parameters by using the MERGE and SOLVE programs. As in GEOSTAR-I, the EIGENVALUE program can be used to analyze the correlations between the elements of the parameter set appearing in a given system of normal equations.

An additional program, ORBGEN has been added to the system which allows for independent analysis and calibration of the integration process and the orbital element sensitivity to particular geopotential coefficients. ORBGEN consists of a modified version of the ODP integration subprogram, ORBIT, together with a driver and subroutine which compute integration performance statistics, such as average stepsize and number of force model evaluations.

The operating method for the orbit generator program is essentially the same as that used for the ODP and is documented in Appendix A1.

III. METHOD

3.1 Geopotential Coefficient Estimation

Essentially, the geopotential coefficients are estimated by augmenting the existing GEOSTAR I ODP normal equations. This augmented system of normal equations is solved within either the framework of the single arc differential correction process or the multiple arc processing using the MERGE/SOLVE programs.

The normal equations in the GEOSTAR-II ODP are of the form

$$[A^T WA + P_0^{-1}]\ \Delta x = A^T W \Delta 0 - P_0^{-1}\ (\Sigma \Delta x) \qquad (1)$$

where if m is the number of observations, and n the number of parameters, then

A = an m $\times$ n matrix of measurement partials with respect to the parameters to be estimated, i.e., $A = \{a_{i,j}\}$, where, if M_i is the i^{th} observation and x_j is the j^{th} parameter to be estimated, then

$$a_{ij} = \frac{\partial M_i}{\partial x_j} \qquad \begin{array}{l} i = 1, 2, \ldots m \\ j = 1, 2, \ldots n \end{array}$$

W = diagonal matrix of measurement weights

P_0 = a-priori covariance matrix on the a-priori estimates of the parameters

Δx = n $\times$ 1 parameter correction vector to be determined

$\Delta 0$ = m $\times$ 1 residual vector

$\Sigma\Delta x$ = the accumulated correction vectors over previous iterations, starting with the a-priori estimates.

In the ODP program, this system can be formed with respect to the satellite state, up to 75 measurement station position coordinates, satellite drag and emissivity factors, measurement biases, and up to 244 geopotential coefficients with a maximum of 250 parameters total.

Matrix equations of the form (1) are then either directly inverted or processed using the MERGE and SOLVE programs for multiple arc solutions as in the GEOSTAR-I system See reference 1 for a detailed description of this process.

3.2 Numerical Integration Starting Procedure

The numerical integration of the equations of motion for position and the associated variational equations for position partials is performed by using a Cowell integration process identical to that used in GEOSTAR-I. The Runge-Kutta type starting procedure however, has been replaced by a more efficient iterative scheme. This process is based on closed form Newtonian-type integration formulas given by

$$\overline{x}_{n+j} = h^2 \left[{}^{II}\overline{S}_n + (j-1) \quad {}^{I}\overline{S}_n + \sum_{i=0}^{k} \alpha_i (j)\, \overline{x}_{n-i} \right]$$

$$\ddot{\bar{x}}_{n+j} = h \left[{}^{I}\bar{S}_n + \sum_{i=0}^{k} \alpha_i^* (j)\, \dot{\bar{x}}_{n-i} \right]$$

where

$\bar{x}_n, \bar{x}_n, \dot{\bar{x}}_n$ = position, velocity and acceleration vectors or vector partials with respect to a parametric being estimated, evaluated at time $t = t_n$,

h = the stepsize to be used in the integration process,

k = $p - 2$, where p is the order of integration process, $k_{nominal} = 10$,

j = an integer which determines which time point is being computed,

${}^{I}\bar{S}_n$, ${}^{II}\bar{S}_n$ = the first and second sums of the acceleration vectors, which can be defined as

$${}^{I}\bar{S}_n = \nabla^{-1} \dot{\bar{x}}_n$$

$${}^{II}\bar{S}_n = \nabla^{-1} \; {}^{I}\bar{S}_n = \nabla^{-2} \dot{\bar{x}}_n,$$

$\alpha_i(j)$, $\alpha_i^*(j)$ = integration coefficients which are functions of j and p.

The coefficients α_i and α_i^* can be defined by integrating the appropriate Newtonian interpolation polynomial. The results can be expressed as

$$\alpha_i (j) = (-1)^i \sum_{\ell=i}^{k} \binom{\ell}{i} \beta''_{\ell+2} (j)$$

$$\alpha_i^* (j) = (-1)^i \sum_{\ell=i}^{k} \binom{\ell}{i} \beta'_{\ell+1} (j)$$

where we have the recursions

$$\beta_i (j) = (-1)^i \binom{-j}{i} = \frac{j + i - 1}{i} \beta_{i-1} (j)$$

$$\beta'_i(0) = -\sum_{\ell=0}^{i-1} \frac{1}{i-\ell+1}\, \beta'_\ell(0)$$

$$\beta'_i(j) = \sum_{\ell=0}^{i} \beta'_\ell(0)\, \beta_{i-\ell}(j)$$

$$\beta''_i(0) = \sum_{\ell=0}^{i} \beta'_\ell(0)\, \beta'_{i-\ell}(0)$$

$$\beta''_i(j) = \sum_{\ell=0}^{i} \beta''_\ell(0)\, \beta_{i-\ell}(s)$$

and $\binom{\ell}{i}$ are binomial coefficients. These formulas are derived in reference 2, see also reference 3.

The starting algorithm is to obtain the values $\bar{x}_i$, $\bar{x}_i$, $\ddot{\bar{x}}_i$, $i = \pm 1, \pm 2, \pm 3, \pm 4, \pm 5$ by successive approximations. Letting $\bar{x}_i^{(\ell)}$ denote the ℓ^{th} approximation, the $(\ell + 1)^{st}$ approximation is given by the following procedure:

(i) compute the sums ${}^{I}\bar{S}_5$, ${}^{II}\bar{S}_5$ using

$$ {}^{I}\bar{S}_5 = \frac{\dot{\bar{x}}_0}{h} - \sum_{i=0}^{10} \alpha^*_i(-5)\, \ddot{\bar{x}}^{(\ell)}_{5-i}$$

$$ {}^{II}\bar{S}_5 = \frac{\bar{x}_0}{h^2} + 6\ {}^{I}\bar{S}_5 - \sum_{i=0}^{10} \alpha_i(-5)\, \dot{\bar{x}}^{(\ell)}_{5-i}$$

(ii) Compute position and velocity vectors

$$x_i^{(\ell+1)} = h^2 \left[{}^{II}\bar{S}_5 + (i-6)\ {}^{I}\bar{S}_5 + \sum_{i=0}^{10} \alpha_i (i-5)\, \ddot{\bar{x}}^{(\ell)}_{5-i} \right]$$

$$\dot{x}_i^{(\ell+1)} = h \left[{}^{I}\overline{S}_5 + \sum_{i=0}^{10} \alpha_i^* \, (i-5) \, \ddot{x}_{5-i}^{(\ell)} \right],$$

$$i = \pm 1, \pm 2, \pm 3, \pm 4, \pm 5$$

(iii) Compute accelerations $\ddot{x}_i^{(\ell+1)}$ using the force model, completling on iteration. Steps (i) → (iii) are repeated until convergence.

For the satellite position and velocity, the 1st approximation ($\ell = 1$) is obtained by converting the epoch position and velocity vectors to Keplerian elements and computing a 2-body solution at the required t_i, $i = \pm 1, \pm 2, \pm 3, \pm 4, \pm 5$, For the variational equations the values of the position and velocity partials at t_i are taken to be equal to their values at t_0.

IV. NEW AND UPDATED MODULES IN GEOSTAR-I SYSTEM

This section describes the modification and additions made to the subroutine structures of the GEOSTAR-I System.

To obtain the GEOSTAR-II ODP the GEOSTAR-I ODP was modified to allow for an increase in the number of geopotential coefficients to be estimated as well as the number of station position coordinates and measurement biases. To accomplish this, the following modules were modified·

MAIN	COEFF	MMATRX	SQUANT
OUTPUT	DRAG	ORB 1	SWTEST
OPTCRD	EGRAV	PREDCT	VEVAL
STATRD	GDET	READGP	ESTIM
BLKSTA	INPUT-BLOCK DATA	SOLVGP	

Additionally, the following modules were developed specifically for the GEOSTAR-II ODP:

For Parameter Estimation: WRITEB, READAP, SYMINV

For Numerical Integration: IBINC, MSCOEF, MSTART, TRANS

To achieve the capability of being able to integrate variational equations for a total of 250 parameters, the following existing GEOSTAR-I orbit generator modules were modified in order to efficiently utilize the space required. Those modules modified are:

ORBIT	HEMINT
CSTEP	SUMS
FRCS	

In the following sections, those modules listed above which are either new or significantly modified existing subroutines will be documented in detail. The remaining modules which received minor modifications are only briefly outlined, with changes indicated. Further details of these, as well as unmodified GEOSTAR-I ODP subroutine can be found in Reference 1.

4.1 Modifications to Existing GEOSTAR-I ODP modules

The modifications made to the GEOSTAR-I ODP executive routine, MAIN, and some of the other existing modules are designed to:

- Call the new subroutines as listed above in proper sequence
- Extend the program options applicable to geopotential coefficients and integration features
- Extend total number of parameters to be estimated to a maximum of 250
- Extend tables to provide space for storing the position partials necessary for parameter estimation
- Sort geopotential coefficients and station coordinates being estimated into an order readily acceptable to the SOLVE program
- Extend program options to allow a-priori values of the drag and solar radiation constants to be different from their respective estimated values
- Keep only the upper triangular portion of the normal equations matrix in core and invert this matrix when requested.

Note WRITEB replaces WTMAT, TRANS replaces POSVEL, and SYMIN replaces DNVERT in the GEOSTAR-I ODP version

A summary of these modifications for the GEOSTAR-II ODP follows

- MAIN – the ODP control program. Modified to control the new subroutines WRITEB, READAP

- DRAG, EGRAV, INPUT, MMATRX, SWTEST, VEVAL – Modified to extend tables for storing the position partials with respect to the geopotential coeffients being estimated

- PREDCT, GDET, ORB 1 – Modified to accommodate the additional measurement partials needed for the additional number of parameters being estimated

- BLKSTA, COEFF, SQUANT – Modified to provide space for additional station position coordinates being estimated

- STATRD – Modified to extend the total number of station position coordinates being estimated to a maximum of 75

- OUTPUT – Modified to include the I/O required for the a priori values of the drag and solar radiation constants

- OPTCRD – Modified to sort* the station position coordinates into the proper order for easy access when creating a B matrix

- READGP – Modified to sort* the geopotential coefficients being estimated into the proper order for easy access when creating a B matrix

- ESTIM – Modified to keep only the upper triangular portion of the normal equations matrix, and to allow a full variance-covariance matrix for state only

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*Sorting was previously done in the subroutine WTBMAT of the GEOSTAR-I ODP

- ORBIT, CSTEP, FRCS, SUMS - Modified to utilize efficiently the space required for the integration of the equation of motion and the variational equations

- HEMINT - Modified to interpolate for the position partials more efficiently.

4.2 New GEOSTAR-II Modules and Significantly Modified GEOSTAR-I ODP Modules

The following GEOSTAR-II ODP modules were written to allow for the use of a-priori estimates for the drag constant, solar radiation constant, and geopotential coefficients, I/O interface requirements with the LUNGFISH MERGE and SOLVE programs; and numerical integration of the equations of motion.

The starting procedure portion of the orbit generator portion of the GEOSTAR-I ODP program was replaced by a new set of subroutines which improves the efficiency of the system. All other routines which comprise the orbit generator portion of the system were modified for more efficient core usage.

Those subroutines effected by the new starting procedure are summarized in Table 1.

Table 1

Replaced GEOSTAR-I ODP Routines	New GEOSTAR-II ODP Routines (approximate equivalents)
TABLE, RK	IBINC, MSCOEF, MSTART

ENTRY 0

Purpose To retrieve the entry point address (EPA) at which the program is loaded into core at execution time.

Called By:

MAIN

Calling Sequence:

CALL ENTRY 0 (KKK1)

Variables Not in Common:

Fortran Name	Format	Description
KKK1	I	Entry point address expressed in decimal. This information is passed by COMMON/ENTRY/ to subroutine OUTPUT where it is printed.

ESTIM

Purpose: Sums all measurement partials into the normal equations matrix and right hand sides for each observation data point. When all observations have been processed a-priori parameter weights (input to the system as parameter sigmas or a full weight matrix) are applied.

Called By:

MAIN

Method:

The normal equations are formed by summing all measurement partials for each observation data point and storing these values into a square matrix. However, since the normal matrix is symmetric, only the upper triangular portion of the matrix needs to be saved. Taking this fact into consideration, it is possible to reduce the matrix storage requirements from n^2 locations to $n(n+1)/2$ locations (where n represents the number of parameters being estimated) by storing the equivalent symmetric two dimensional array into a single dimensioned array. Corresponding array locations in the single dimensioned array S1,* are computed from the function

$$KI(I, J) = MATD(I-1) + J - (I-1)I/2 \tag{1}$$

where $J \geq I$ and MATD is the total number of parameters to be estimated.

In addition to this change, the subroutine was further modified so that a non-diagonal a-priori variance – covariance matrix is allowed only for the orbital elements.**

*The S1 single dimensioned array corresponds to the two dimensional array SUM1 in the GEOSTAR-I ODP

**GEOSTAR-I ODP on option allowed a full variance – covariance matrix for all the parameters being estimated

Calling Sequence·

CALLESTIM(ITYPE,SIGMA,RESID, PMPX0, PMPSTA, ISTA1, INDXBS, INDXTM, TPART, MATD)

COMMON Blocks Used.

CONST1	NON2
CELEM	SETSW
CQUANT	SEQ
PRIORI	HELP
ESTGP	NON4

Variables Not in COMMON:

FORTRAN Name	Format	Description
ITYPE	I	1 = Initialization, 2 = Increment, 3 = Add a-priori information
SIGMA	R	Measurement sigma
RESID	R	Measurement residual
PMPXO (8)	D	Array of measurement partials with respect to satellite parameters ($\partial M/\partial X_0$)
PMPSTA (3)	D	Array of measurement partials with respect to station position ($\partial M/\partial S$)
ISTA1	I	Total number of stations to be estimated in initialization
INDXBS	I	Array index for measurement bias
INDXTM	I	Array index for measurement timing bias
TPART	R	Measurement partial with respect to timing bias ($\partial M/\partial B$)
MATD	I	Total number of parameters to be estimated.

FORTRAN Name	Format	Description
NPAR	I	Number of satellite parameters to be estimated
NSTA	I	Total number of measurement stations to be estimated.
NOEST		True if measurement station is not to be estimated

IBINC

Purpose: To compute the binomial coefficients needed to compute the coefficients for the multistep starter formulas.

Called By:

MSCOEF

Method:

IBINC computs by addition, a (n + 1) × (n + 1) matrix, BC, containing Pascal's triangle. All upper triangular elements above the major diagonal are zero. Any binomial coefficient $\binom{n}{i}$ up to $\binom{n}{n}$ can be selected from this matrix by the indices (i + 1, n + 1).

Calling Sequence:

CALL IBINC (N, BC)

Variables Not in COMMON:

FORTRAN Name	Format	Description
BC (n + 1, n + 1)	D	Binomial
N	I	coefficient order

MSCOEF

Purpose. To compute the coefficients needed for the multistep starter formulas.

Called By:

MSTART

Calls

IBINC

Method

The coefficients α_i , α_i^* for the formulas

$$x\,(t + s\,h) = h^2 \Bigg[\nabla^{-2}\, x\,(t) + (s - 1)\, \nabla^{-1}\, \dot{x}\,(t)$$

$$+ \sum_{i=0}^{n} \alpha_i\,(s)\, x\,(t - i\,h) \Bigg]$$

$$x\,(t + s\,h) = h \left[\nabla^{-1}\, \ddot{x}\,(t) + \sum_{i=0}^{n} \alpha_i^*\,(s)\, \dot{x}\,(t - i\,h) \right]$$

are computed, for any s, by the following:

$$\alpha_i\,(s) = (-1)^i \sum_{\ell=i}^{n} \binom{\ell}{i} \beta''_{\ell+2}\,(s)$$

$$\alpha_i^*\,(s) = (-1)^i \sum_{\ell=i}^{n} \binom{\ell}{i} \beta''_{\ell+1}\,(s)$$

$$i = 0,\ 1,\ 2,\ \cdot \quad\quad n$$

where $\binom{\ell}{i}$ are the binomial coefficients and where the β''_i (s), β'_i (s) are obtained by the formulas

$$\beta'_i\,(s) = \sum_{\ell=0}^{i} \beta'_\ell\,(0)\, \beta_{i-\ell}\,(s)$$

$$\beta''_i\,(s) = \sum_{\ell=0}^{i} \beta''_\ell\,(0)\, \beta_{i-\ell}\,(s)$$

where

$$\beta_i \ (s) = (-1)^i \binom{-s}{i}$$

$$\beta_i' \ (0) = -\sum_{\ell=0}^{i-1} \frac{1}{i - \ell + 1} \ \beta_\ell' \ (0)$$

$$\beta_i'' \ (0) = \sum_{\ell=0}^{i} \beta_\ell' \ (0) \ \beta_{i-\ell}' \ (0)$$

$$i = 1, \ 2, \qquad .$$

and

$$\beta_0' \ (0) = \beta_0'' \ (0) = \beta_0' \ (s) = \beta_0'' \ (s) = 1$$

Calling Sequence:

CALL MSCOEF (M,N)

COMMON Block Used:

MCOEFF

Variables Not in COMMON:

FORTRAN Name	Format	Description
M	I	M = -s
N	I	Number of coefficients to be generated.
BPZERO (20)	D	$\beta'(0)$
BIS (20)	D	$\beta_1(s)$
BPS (20)	D	$\beta_1'(s)$
BDPZ (20)	D	$\beta_1''(0)$
BDPS (20)	D	$\beta_1''(s)$
BINCI (16, 16)	D	Binomial coefficients

MSTART

Purpose: To compute the required starting values for the integration of the equations of motion and the variational equations using an iterative procedure based on closed form multistep formulas.

Called By.

ORBIT

Calls

TRANS
FRCS
VEVAL
MSCOEF

Method

An iterative process based on the closed form of the Newtonian-type integration formulas is used to compute the required starting arrays of accelerations and acceleration partials. These formulas are given by:

$$\bar{x}_{n+j}^{(\ell+1)} = h^2 \left[{}^{II}\bar{S}_n^{(\ell)} + (j - 1)\, {}^{I}\bar{S}_n^{(\ell)} + \sum_{i=0}^{k} \alpha_i (j)\, \ddot{\bar{x}}_{n-i}^{(\ell)} \right] \tag{1}$$

$$\dot{\bar{x}}_{n+j}^{(\ell+1)} = h \left[{}^{I}\bar{S}_n^{(\ell)} + \sum_{i=0}^{k} \alpha_i^* (j)\, \ddot{\bar{x}}_{n-i}^{(\ell)} \right] \tag{2}$$

where

$${}^{I}\bar{S}_n^{(\ell)} = \nabla^{-1} \dot{\bar{x}}_n^{(\ell)}$$

$${}^{II}\bar{S}_n^{(\ell)} = \nabla^{-2} \bar{x}_n^{(\ell)}$$

Initial first approximations for $\bar{x}_i^{(1)}, \dot{\bar{x}}_i^{(1)}, \ddot{\bar{x}}_i^{(1)}$, $i = \pm 1, 2, 3, 4, 5$ are obtained using a 2-body solution. Next, the first and second sums, ${}^{I}\bar{S}_5$, ${}^{II}\bar{S}_5$ are computed and used in equations (1) and (2) to obtain corrected values for position and velocity, $\bar{x}^{(\ell+1)}$, $\bar{x}^{(\ell+1)}$ Corrected value of the accelerations are computed whenever a successive correction is necessary.

Calling Sequence:

CALL MSTART (IEQ)

COMMON Blocks Used:

WORKER
ANPART
GRBLOK
XYZ
MCOEFF
LIMITS

Variables Not in COMMON:

FORTRAN Name	Format	Description
M	I	k
MN	I	k/2
TX (3)	D	Components of position vector
TXD (3)	D	Components of velocity vector
TR	D	Time of interest
ITER	I	Number of iterations needed to produce starting arrays
MNI	I	M-I
S1 (3, 50)	D	First sum array
S2 (3, 50)	D	Second sum array
SCDX (3)	D	Corrected value of position or position partials
SCOXD	D	Corrected value of velocity or velocity partials
SUMI	D	Intermediate quantity in computation of position vectors

FORMAT Name	Format	Description
SUM2	D	Intermediate quantity in computation of velocity vectors
RBAR	D	Square root of the sum of the squares of the components of the position vectors
SUM	D	Maximum value of the corrector components for the position vectors
SUM3	D	Maximum value of SUN/RBAR for all the position vectors
EST (15)	D	Largest correction component of all equations for each starting position vector produced
SXDD (3, 20)	D	Saved values of acceleration vectors for all equations

READAP

Purpose: To read in data to modify the prestored a-priori values and stored sigma values for the geopotential coefficients

Called By:

OPTCRD

Method

The call to READAP is initiated by the APRIOR option card. Additional cards which contain the coefficient name and/or an a-priori value and/or a sigma value are used to replace the prestored data in COMMON/ESTGP/.

Calling Sequence:

CALL READAP (INTP, IARRAY, DT1, T2, T3, T4, T5)

COMMON Blocks Used

ESTGP

Variables Not in COMMON.

FORTRAN Name	Format	Description
INTP	I	INPUT set, usually FT05
IRRAY (4)	I	Not used
DT1, T2, T3, T4, T5	D	Not used
VAL	R	A-priori value for the geopotential coefficient
SIG	R	Sigma value for the geopotential coefficient

SYMINV

Purpose: To invert a symmetric matrix stored in a single dimensional array.

Called by:

SOLVGP

Method

The Gauss-Jordan method of condensation with partial (column) pivoting is used
The inversion is performed on a single dimensional array containing the upper triangular portion of the symmetric matrix.

Calling Sequence·

CALL SYMINV (S1, NPARAM, NPARAM, DELTA)

Variables:

FORTRAN Name	Format	Description
S1(31375)	D	Input matrix to be inverted and output inverted matrix
NPARAM	I	Total number of unknowns to be estimated
DELTA (250)	D	Dummy array

TRANS

Purpose: To convert osculating 2-body orbital elements at epoch to inertial position and velocity vectors at time $t \geq t_o$.

Called By:

MAIN
MSTART

Method:

Given the Keplerian orbital elements at epoch ($t = t_0$)

a_0 = semi-major axis

e_0 = eccentricity

i_0 = inclination

ℓ_0 = mean anomaly

g_0 = argument of perigee

h_0 = argument of node

and a time t, a 2-body position and velocity vector is computed by:

(a) computing the mean anomaly

$$\ell = \ell_0 + n\,(t - t_0)$$

where

$$n = \sqrt{\frac{GM}{a^3}},$$

GM the gravitational constant times mass of the earth,

(b) Using this mean anomaly ℓ, solve Kepler's equation

$$E - e \sin E = \ell$$

by successive approximation for the eccentric anomaly E,

(c) Compute vectors $\overline{P}, \overline{Q}$ by

$$P_x = \cos g_0 \cos h_0 - \sin g_0 \sin h_0 \cos I_0$$

$$P_y = \sin g_0 \cos h_0 \cos I_0 + \cos g_0 \sin h_0$$

$$P_z = \sin g_0 \sin I_0$$

$$Q_x = -\sin g_0 \cos h_0 - \cos g_0 \sin h_0 \cos I_0$$

$$Q_y = \cos g_0 \cos h_0 \cos I_0 - \sin g_0 \sin h_0$$

$$Q_z = \cos g_0 \sin I_0$$

(d) Compute position and velocity vectors $[\overline{x}, \overline{x}]$ by:

$$\overline{x} = a_0 \begin{bmatrix} P_x & \sqrt{1-e_0^2} & Q_x \\ P_y & \sqrt{1-e_0^2} & Q_y \\ P_z & \sqrt{1-e_0^2} & Q_z \end{bmatrix}_{3\times 2} \begin{bmatrix} \cos E - e_0 \\ \sin E \end{bmatrix}_{2\times 1}$$

$$\overline{x} = \left(\frac{n\, a_0}{1 - e_0 \cos E}\right) \begin{bmatrix} \sqrt{1-e_0^2} & Q_x & -P_x \\ \sqrt{1-e_0^2} & Q_y & -P_y \\ \sqrt{1-e_0^2} & Q_z & -P_z \end{bmatrix} \begin{bmatrix} \cos E \\ \sin E \end{bmatrix}$$

Calling Sequence:

CALL TRANS (T, TX, TXD)

COMMON Blocks Used·

SCELEM
CONST[1]

Variables Not in COMMON:

FORTRAN Name	Format	Description
T	D	Request Time
TX (3)	D	Rectangular components of the position vector
TXD (3)	D	Rectangular components of the velocity vector
ELEM (1)	D	a_0
ELEM (2)	D	e_0
ELEM (3)	D	I_0
ELEM (4)	D	ℓ_0
ELEM (5)	D	g_0
ELEM (6)	D	h_0
N	D	$\sqrt{\frac{GM}{a^3}}$
L	D	Mean anomaly
E	D	E
DE	D	SE
D	D	$\frac{n}{1 - e \cos E}$
P (3)	D	$\bar{P}$

Fortran Name	Format	Description
Q (3)	D	$\overline{Q}$
RXV	D	$\lvert \overline{x} \times \dot{\overline{x}} \rvert$

WRITEB

Purpose: To output on a specified device the normal equations, together with the latest values and the labels of the parameters, in the SOLVE B matrix format.

Called By:

MAIN

Method:

The parameter sequence of the normal equations in the GEOSTAR-II ODP is different from that required by the SOLVE B matrix format (see Reference 1). The subprogram WRITEB creates a new normal equation matrix in the B matrix format by transferring rows and columns from the original GEOSTAR-II ODP matrix. Blocks of data for a particular parameter type are shifted, one at a time, into the designated B matrix areas. In order to conserve space, the new matrix in the B matrix format overlays the area previously used to store the integration arrays.

WRITEB also takes each parameter type group, and assigns labels and sorts the parameters into the B matrix format within each particular parameter group. The right hand side of the normal equations, is also in a different sequence from that required by the B matrix format, and is shifted into the designated arrangement. Again, to conserve space, the new right hand side in the B matrix format overlays the area previously used to store the first sums needed in the integrator. After the shifting, sorting, and labeling has taken place, the normal equations matrix is written by rows in the B matrix format.

The total variance, as required by the SOLVE program, is computed as:

$$V1 = (RMS)^2 * [NOB - (NPARAM - 1)]$$

where

RMS = total weighted standard deviation

NOB = total number of observations used

NPARAM = total number of parameters being estimated.

Calling Sequence:

CALL WRITEB (RMSTOT, NOWTOB, NSTEST, NBIAS, BNAME, BMT)

COMMON Blocks Used:

SEQ	ESTGP
HELP	CELEM
NON2	PRIORI
STANUM	LIMITS
CONST1	WORKER

Variables Not In Common:

FORTRAN Name	Format	Description
RMSTOT	R	Total weighted standard deviation
NOWTOB	I	NOB, number of weighted observations used in computing RMSTOT
NSTEST	I	Number of stations whose coordinates are to be estimated
NBIAS	I	Number of bias parameters parameters
BNAME (3)	R	B matrix name (12 EBCDIC characters)
BMT	I	Output data set reference number
V1, V2	D	Total variance
NPARAM	I	Total number of parameters to be estimated
BMATRX (31375)	D	The normal equations in the SOLVE B matrix format
BRHS (250)	D	The right hand side in the SOLVE B matrix format
SBUF (250)	D	Dummy storage arrays

V. COMMON BLOCK VARIABLE DESCRIPTION

The following sections contain the COMMON block descriptions of the new COMMON areas used in the GEOSTAR-II ODP. These descriptions include the variables contained in these areas, their type and meaning, and the subroutines which either define or use these variables. Also, following the section of the COMMON block variable descriptions, a section containing a cross reference table of all the COMMON areas as used in each subroutine is presented.

5 1 Modified GEOSTAR-I ODP COMMON Blocks

This section contains the names of the COMMON Blocks, the variable names and the dimensions of those variables that were changed from the GEOSTAR-I ODP for the GEOSTAR-II ODP.

COMMON/SCRTCH/	PSIG (3,3,25)
COMMON/SEQ/	SUM2 (250), PARAMS (250), LABEL (250)
COMMON/CPARTL/	PXPX0 (250,6) PMPX0 (250,2)
COMMON/NON1/	PLHSW (25)
COMMON/NON3/	TTL (250)
COMMON/NON4/	BSEND (244), BSTRT (244), BYTPE (244), BSTANO (244), ISTEST (25)
COMMON/NON6/	XYZNOM (25,6), PLHNOM (25,6), HN (25), SLATN (25), LATDN (25), LATMN (25), LONDN (25), LONMN (25), SLONN (25)
COMMON/ESTGP/	CSA (250), CSE (250), CSSIG (250), NCSN (250), NCSM (250)
COMMON/PRIORI/	STASIG (3,3,25), PLHSIG (3,3,25), XSTA (25), YSTA (25), ZSTA (25), PBIAS (244), BIAS0 (244), BIASSG (244)
COMMON/LIMITS/	S1 (3, 250), S2 (3, 250)
COMMON/WORKER/	X(6,3,250), XD (6, 3, 250), XDD (20, 3, 250) XXDD (3,250), VRCOV*(14000), JHIGH*, VRCSW*

NOTES

COMMON/PRIOR/	Written over in CSTEP
COMMON/LIMITS/	Written over in MAIN
COMMON/WORKER/	*Dummy array and dummy variables used to increase the size of the COMMON block. This was done because the subroutine WRITEB uses this area when the normal equations matrix is put into the B matrix format.

5.2 New GEOSTAR-II ODP COMMON Blocks

This section contains a description of the new COMMON areas used in the GEOSTAR-II ODP program.

/ENTRY/

COMMON/ENTRY/KKK 1

Variable Name	Format	Description	Program Where Defined	Program Where Used
KKK1	I	Entry point address where the program is loaded into core at execution time.	MAIN	OUTPUT

/HELP/

COMMON/HELP/S1 (31375)

Variable Name	Format	Description	Program Where Defined	Program Where Used
S1 (31375)	D	Normal equations matrix	ESTIM	MAIN ESTIM SOLVGP WRITEB ORBIT MSTART

During the initialization process of the integrator, the storage area in COMMON/HELP/ is utilized by subroutine MSTART to store temporary integration arrays. The subroutine ESTIM then overlays this area with the normal equations matrix. After solution, the matrix S1 (31375) contains the variance-covariance matrix of all parameters which are adjusted by the differential correction.

/IPERS/

COMMON/IPERS/ITRS, NSTEP

Variable Name	Format	Description	Program Where Defined	Program Where Used
ITRS	I	Total number of predictor-corrector iterations for equations of motion in CSTEP	ORBIT	CSTEP MAIN
NSTEP	I	Total number of Cowell steps for the equations of motion	ORBIT	CSTEP MAIN

/MCOEFF/

COMMON/MCOEFF/SBPS(16), SBDPS (16), STOL, II, 12, N00

Variable Name	Format	Description	Program Where Defined	Program Where Used
SBPS (16)	D	Coefficients for multistep starter equations to compute positions	MSCOEF	MSTART
SBDPS (16)	D	Coefficients for multistep starter equations to compute velocities	MSCOEF	MSTART
STOL	D	Convergence criteria	BLOCK DATA OPTCRD (initialized to 1.0×10^{-13})	MSTART OUTPUT
I1	I	Value zero	MSCOEF	MSTART
I2	I	Value zero	MSCOEF	MSTART
N00	I	Total number of iterations allowed	BLOCK DATA OPTCRD (initialized to 15)	MSTART

/SCLEM/

COMMON/SCELEM/ORBEPC (6)

Variable Name	Format	Description	Program Where Defined	Program Where Used
			Orbital Elements - Osculating Keplerian	
ORBEPC (1)	D	Semi-major axis-meters	MAIN	TRANS
ORBEPC (2)	D	Eccentricity	MAIN	TRANS
ORBEPC (3)	D	Inclination-radians	MAIN	TRANS
ORBEPC (4)	D	Longitude of ascending node-radians	MAIN	TRANS
ORBEPC (5)	D	Argument of percenter-radians	MAIN	TRANS
ORBEPC (6)	D	Mean anomaly-radians	MAIN	TRANS

/SEQ/*

COMMON/SEQ/SUM2(250), PARAMS(250), LABEL(250), IDMAT

Variable	Type	Description	Program Where Defined	Program Where Used
SUM2(250)	D	Right hand side of normal equations in GEOSTAR-II ODP parameter order	ESTIM	ESTIM WRITEB SOLVGP
PARAMS	D	Parameter values in B matrix order by row	WRITEB	WRITEB
LABEL(250)	I	Numberical identifiers for the type of parameters in PARAMS, in the same order	WRITEB	READGP WRITEB
IDMAT	I	B matrix identification number.	OPTCRD	WRITEB OUTPUT

* Replaces COMMON/BEQ/of the GEOSTAR-I ODP

/SINIT/

COMMON/SINIT/ITERSW

Variable	Type	Description	Program where Defined	Program where Used
ITERSW	L	Switch to initialize the starter for each iteration	ORBIT	MSTART

5.3 GEOSTAR-II ODP COMMON Block Cross Reference Table

This section contains a cross reference table describing the COMMON area structure in the GEOSTAR-II ODP.

GEOSTAR-II COMMON Cross Reference Table

SUBROUTINES

COMMON BLOCKS	MAIN	APPER	BLKSTA	BLDAT1	BLDAT2	BLDAT3	COIII	COIIL	CSIFP	DINSIY	DODSRD	DRAG	ICRAV	FLFM	FLEMK	IPHQAN	IRROR	ESTIM	FRCS	GDFT	GFOSRD	HFMINT	INV2	MSCOEF	MSTART	OBSDOT	OPTCRD	ORB1	ORBIT	OUTPUT
ABCOEF					x				x																				x	
ANPART									x																x				x	
CLLEM	x	x												x				x									x	x		
CGEOS	x										x										x						x	x		
COIIT	x				x											x			x										x	
CONST1	x	x			x						x	x		x	x			x	x								x	x	x	x
CONST2	x				x					x	x			x	x						x						x	x	x	
CONST3	x	x										x				x			x									x	x	
CONVRG	x																										x		x	x
CORB1	x	x																										x		
COSAVE					x											x			x											
CPARTL	x																			x										
CQUANT	x		x	x														x								x				
CSTINE	x																													
DC																							x							
DRGBLK										x		x																		
ENTRY	x																													x
ESTGP	x												x					x									x		x	x
FLXBLK	x									x	x								x		x						x	x		
FMODEL	x				x			x					x														x	x		x
GRBLOK									x			x	x						x										x	
HELP	x																	x							x				x	
IORBIT	x												x												x			x	x	
IPERS	x								x																				x	
LIMITS	x				x				x				x						x			x			x		x	x	x	x
HCOFTF	x				x																			x	x		x			x
NON1	x				x																						x			
NON2	x				x													x									x		x	
NON3	x				x																						x			
NON4	x				x													x									x			
NON5	x				x																						x			
NON6	x																													
OUTFOR	x																													x
PCES	x																										x			x
PCOFIT					x											x														
PREBLK	x										x										x						x			
PRIORI	x					x			x									x									x			x
SCELEM	x																												x	x
SCRTCH	x		x				x																				x			
SEQ	x				x													x									x			x
SETSW	x								x			x	x					x	x										x	
SIGMAC				x							x										x						x			
SINIT																									x				x	
STANUM	x		x								x										x									
VRBLOK					x								x																	
WORKER	x				x				x										x			x			x		x		x	x
XYZ									x	x		x	x						x						x				x	
XYZOUT	x																									x			x	

GEOSTAR-I COMMON Block Cross Reference Table (continued)

SUBROUTINES

COMMON BLOCKS	PLHOUT	PREDCT	PRNTPR	PROCES	READAP	READGP	REFIMP	REFCOR	SOLVGP	SQUANT	STAINF	STATRD	STORGP	SUMS	SUNGRV	SWTEST	TRANS	VEVAL	WRITEB	XEFIX	XINERT	YEFIX	YINERT
ABCOEF														x									
ANPART																		x					
CELEM																			x				
CGEOS								x				x											
COFIT		x																x					
CONST1	x	x								x		x					x	x	x				
CONST2		x										x											
CONST3		x		x											x			x					
CONVRG												x											
CPARTL		x																					
CQUANT	x	x					x			x		x											
CSTHET		x																		x	x	x	x
CSTINF											x												
CSVEVL													x					x					
DRGBLK																		x					
ESTGP		x			x	x						x				x		x	x				
FLXBLK		x																x					
FMODEL						x							x										
GRBLOK																		x					
HELP									x										x				
LIMITS		x										x		x		x		x	x				
MOONGR															x			x					
NON1												x											
NON2		x				x						x							x				
NON3												x											
NON4												x											
NON5												x											
NON6												x											
PCES		x										x											
PREBLK			x	x																			
PRIORI									x	x		x							x				
SCELEM																	x						
SCRTCH										x		x											
SEQ						x			x										x				
SETSW																x		x					
SIGMAC												x											
STANUM	x						x					x							x				
VRBLOK																		x					
WORKER														x		x	x		x				
XYZ																		x					
XYZOUT		x		x																			

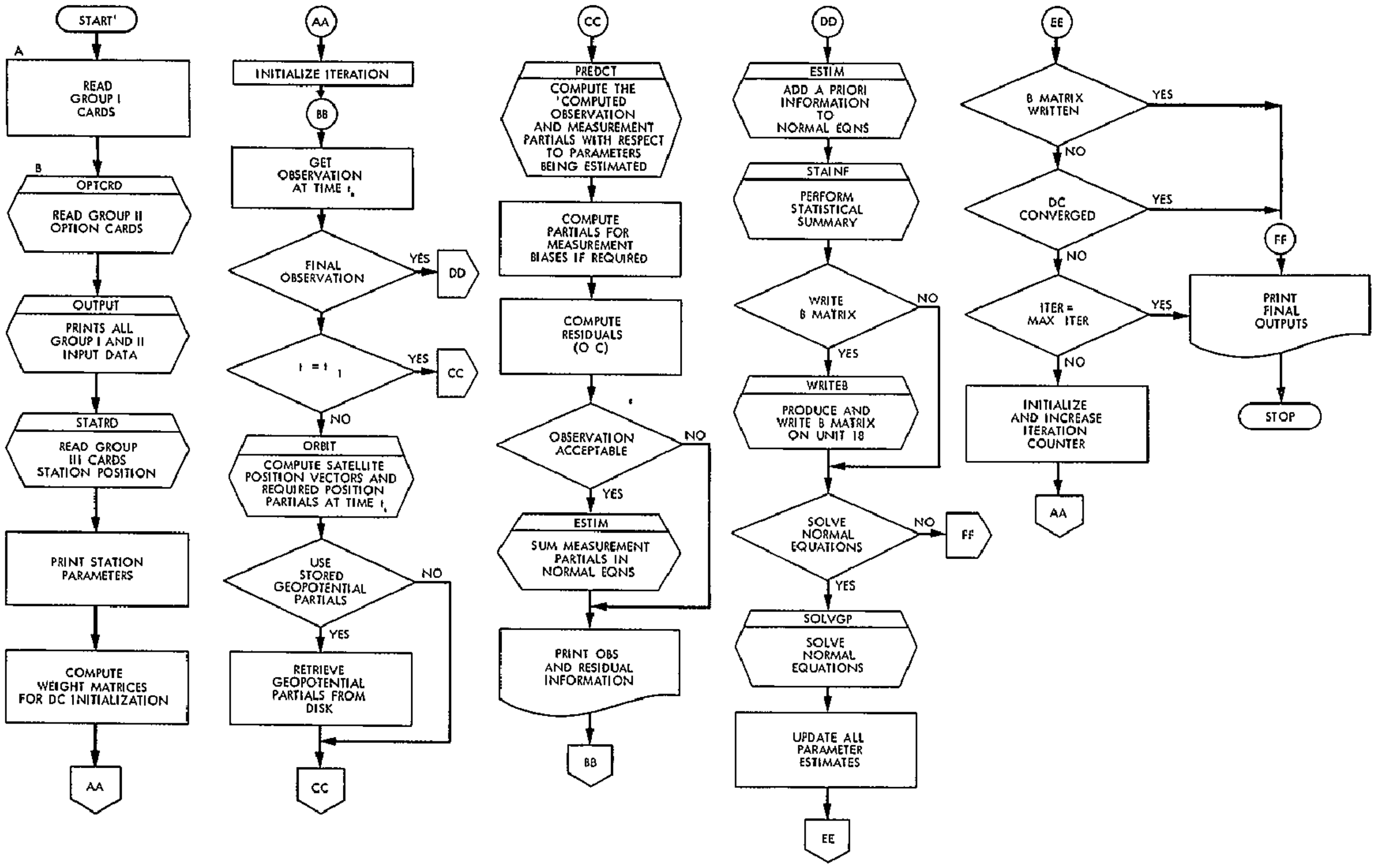
VI. PROGRAM FLOW CHARTS AND SUBROUTINE SUMMARIES

The following sections contain the flow diagrams of the main control routines in the GEOSTAR-II ODP and summary of new modules used in the program. Cross reference tables detailing the entire subroutine structure of the GEOSTAR-II ODP is also presented.

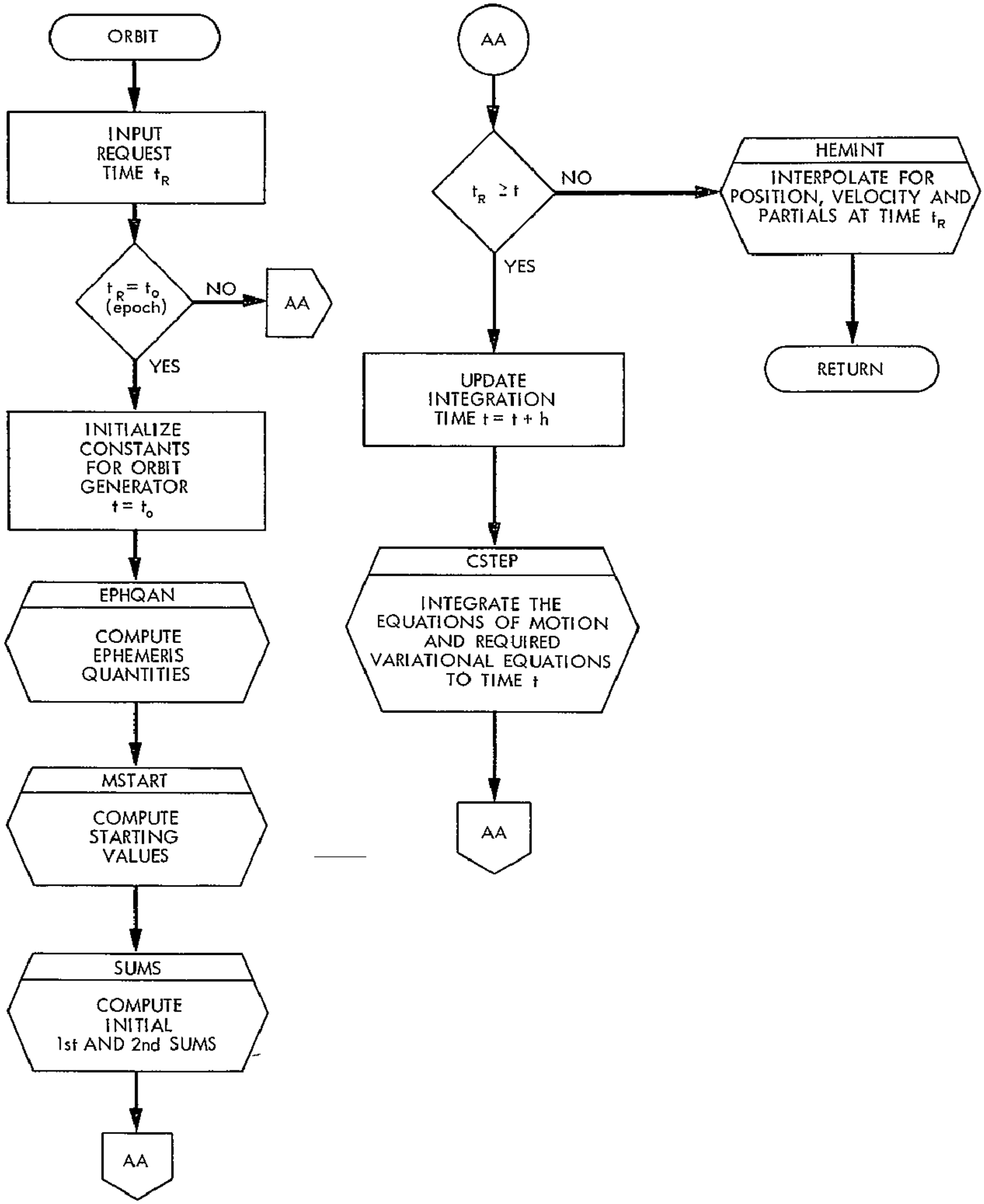
6.1 GEOSTAR-II ODP Flow Diagrams

This section contains the flow diagrams of the GEOSTAR-II ODP executive program MAIN and the orbit generator control subprogram ORBIT.

MAIN PROGRAM



ORBIT SUBROUTINE



6.2 GEOSTAR-II ODP Subroutine Summary

This section contains a brief summary of the new modules used in the GEOSTAR-II ODP. Complete documentation of the GEOSTAR-I ODP modules can be found in Reference 1.

Subroutine Summary

ENTRY0	Retrieves the entry point address (EPA) at which the program is loaded into core at execution time.
IBINC	Computes the binomial coefficients needed to compute the coefficient for the multistep starter formulas.
MSCOEF	Computes the coefficients needed for the multistep starter formulas.
MSTART	Computes the required starting values for the integration of the equations of motion and the variational equations using an iterative procedure based on closed form multistep formulas.
READAP	Modifies prestored a-priori and sigma values for the geopotential coefficients.
SYMINV	Inverts a symmetric matrix which is stored in a single dimensioned array. No restrictions on the dimension of the input matrix.
TRANS	Converts osculating 2-body orbital elements at epoch to inertial position and velocity vector at time, $t \geq t_0$.

6.3 GEOSTAR-II ODP Subroutine Cross Reference Tables

This section contains cross reference tables detailing the subroutine structure in the GEOSTAR-II ODP executive program MAIN and the orbit generator control subprogram ORBIT.

MAIN Program Cross Reference Table

CALLING SUBROUTINES (columns) / CALLED SUBROUTINES (rows)

	MAIN	BLKSTA	COEFF	CSTEP	DATES	DAYEAR	DENSTY	DIFF	DJUL	DODSRD	DRAG	ELEM	EPHQAN	EQUATR	FRCS	GEOSRD	MSCOEF	MSTART	NUTATE	OBSDOT	OPTCRD	ORB1
ADDYMD					x																	
AND2										x												
APPER	x																					
COEFF													x									
COEFL	x																					
DARCTN										x												
DATES	x					x																x
DAYEAR																						x
DENMUL							x															
DENSITY											x											
DIFF	x																					
DINRAD																x						
DJUL													x									x
DODSRD	x														x							
DOTPRD	x														x							x
DRAG															x							
EGRAV																						
ELEM	x																					
ELEMK	x																					
ENTRY0	x																					
EQN													x						x			x
EQUATR										x						x						
ERROR	x											x									x	
ESTIM	x																					
FRCS				x																		
GDET	x																					
GEOSRD	x																					
GTIMIN	x																					
GTIMOT	x																					
HEMINT				x																		
IBINC																	x					
INV2				x																		
INV3	x		x																			
MATRIX				x																		
MOONAD													x									
MSCOEF																		x				
MULMAT																			x			
NUMBER	x	x								x						x					x	
NUTATE														x								
OBSDOT	x																					
OPTCRD	x																					
ORBI	x																					
ORBIT	x																					x
OUTPUT	x																					
PRECES														x								
PREDCT	x																					
READAP	x																				x	
READGP																						
REFCOR															x							
ROTMAT																			x			
RYMDI								x														x
SATCL2																x						
SATCLX																x						
SDOLL																x						
SDTPRD																				x		
SOLVGP	x																					
SQUANT	x																					
STAINF	x																					
STATRD	x																					
STORGP	x																					
SUN													x									
SUNGRV															x							
SYMMET																					x	
TDIF	x				x					x			x			x					x	x
TRANS	x																					
VEVAL				x																		
WRITEB	x																					
XEFIX																				x		
XINERT																				x		
YEFIX																				x		
YINERT																				x		
YMDAY	x								x	x						x			x		x	

MAIN Program Cross Reference Table (continued)

CALLING SUBROUTINES (columns); CALLED SUBROUTINES (rows)

	ORBIT	PLHOUT	PRECES	PREDCT	PROCES	REFCOR	REFIMP	SATCL2	SATCLC	SOLVGP	SQUANT	STAINF	STATRD	TDIF	VEVAL	YMDAY
BLKSTA													x			
CLEAR												x				
COEFL													x			
CSTEP	x															
DARCTN				x												
DATES													x			
DENSITY															x	
DIFF																x
DINRAD											x					
DOTPRD				x	x										x	
EGRAV															x	
EPHQAN	x															
FIT				x												
FRCS	x															
HEMINT	x															
MSTART	x															
MULMAT			x			x										
NUMBER							x						x			
NUTATE						x										
OBSDOT					x											
OUTRAD											x					
PLHOUT											x		x			
PRECES						x										
PRNTPR													x			
PROCES				x												
REFCOR	x														x	
REFIMP					x											
ROTMAT			x													
SQUANT													x			
SUMS	x															
SWTEST	x															
SYMINV																
VCONV		x											x			
VEVAL	x															
XEFIX				x												
XINERT				x												
YEFIX				x												
YINERT				x												
YMDAY			x					x	x					x		

MAIN Program Cross Reference Table (continued)

CALLED SUBROUTINES \ CALLING SUBROUTINES	ORBIT	COEFF	CSTEP	DENSTY	DIFF	DJUL	DRAG	EPHQAN	FRCS	MSCOEF	MSTART	NUTATE	PRECES	REFCOR	VEVAL	YMDAY
COEFF								x								
CSTEP	x															
DENMUL				X												
DENSTY							x								x	
DIFF																x
DJUL								x								
DOTPRD									x						x	
DRAG									x							
EGRAV									x						x	
EPHQAN	x															
EQN								x				x				
FRCS	x		x								x					
HEMINT	x		x													
IBINC										x						
INV2			x													
INV3		x														
MMATRIX			x													
MOONAD								x								
MSCOEF	x															
MSTART											x					
MULMAT												x	x	x		
NUTATE														x		
PRECES														x		
PRIORI			x													
REFCOR	x								x						x	
ROTMAT												x	x			
RYMD1					x											
SUMS	x															
SUN								x								
SUNGRV									x							
SWTEST	x															
TDIF								x								
TRANS											x					
VEVAL	x		x								x					
YMDAY						x						x	x			

VII. ORBGEN

7.1 Introduction

This section describes the modifications and additions made to the subroutine structures of the variable stepsize verison of GEOSTAR-I ODP in order to create a stand-alone orbit generator program, ORBGEN.

The ORBGEN program can optionally numerically integrate the variational equations as well as the equations of motion. The limits on the types of variational equations are as follows:

(a) all parameters - 20
(b) gravity coefficients - 20
(c) state parameters - 6
(d) drag parameters - 1
(e) solar radiation parameters - 1.

The partials are available with respect to either rectangular or Keplerian elements. Also, osculating orbital elements are available at each output step.

The program can operate in either a fixed or variable stepsize mode. In the vary step mode, a resume of stepsize distribution over the integrated trajectory will be output. In the fixed step mode, different stepsizes can be used for the equations of motion and variational equations. Different orders can be used in either mode.

Various force model options are available for the integrations. Using the elliptic motion option, accumulated error estimates are computed by comparing with an analytic 2-body trajectory.

7.2 New and Updated Modules in GEOSTAR-I ODP

To obtain ORBGEN the following GEOSTAR-I ODP modules were modified·

MAIN	CSTEP	VEVAL
OPTCRD	TEST	MSTART
ORBIT	FRCS	

In addition, the following modules were developed specifically for ORBGEN:

RESUME
WRITER
APART

In the following sections, those modules listed above which are new, or significantly modified existing subroutines well be documented in detail. The remaining modules which received only minor modifications are briefly outlined, with changes indicated.

7.3 Modifications to Existing GEOSTAR-I ODP Modules

The modifications made to the GEOSTAR-I ODP are designed to

- Call the new subroutines
- Retain only the subroutines, logic, and output pertinent to an orbit generator program
- Integrate in a UTC time system

A summary of these modules, as modified for ORGBEN follows:

- MAIN — The program control module. Modified to control only the integration of an orbit and associated variational equations.
- OPTCRD — Modified to include an option to integrate in the A1 time system
- ORBIT, CSTEP, TEST, FRCS, VEVAL, MSTART — Modified to save various quantities which are used to compute a statistical summary at the end of a run

7.4 New ORBGEN Modules

These modules were written to allow for the computation of partials with respect to Keplerian elements as well as to accumulate a statistical summary of the integration performance

APART

Purpose: To compute the Jacobian of the osculating Keplerian elements with respect to rectangular coordinates.

Called by:

WRITER

Calls:

INV2

Method

The Jacobian

$$\frac{\partial\,(a,\ e,\ i,\ \Omega,\ \omega,\ M)}{\partial\,(x,\ y,\ z,\ \dot{x},\ \dot{y},\ z)}$$

is computed by inverting the 6 × 6 matrix

$$\begin{bmatrix} \dfrac{\partial\,(x,\ y,\ z)}{\partial\,(a,\ e,\ i)} & \dfrac{\partial\,(x,\ y,\ z)}{\partial\,(\Omega,\ \omega,\ M)} \\ \\ \dfrac{\partial\,(x,\ \dot{y},\ z)}{\partial\,(a,\ e,\ i)} & \dfrac{\partial\,(x,\ \dot{y},\ z)}{\partial\,(\Omega,\ \omega,\ M)} \end{bmatrix},$$

The required partials can be derived from the relations

$$\overline{x} = R_{xq}\,(\Omega,\ \omega,\ \omega)\ \overline{q}\,(a,\ e,\ M)$$

$$\dot{\overline{x}} = R_{xq}\,(\Omega,\ i,\ \omega)\ \dot{\overline{q}}\,(a,\ e,\ M)$$

where

$$q = \begin{bmatrix} a\,(\cos E - e) \\ a\sqrt{1 - e^2}\ \sin E, \\ 0 \end{bmatrix}, \qquad q = \frac{\mu\ a}{1 - e\cos E}\begin{bmatrix} -\sin E \\ \sqrt{1 - e^2}\ \cos E \\ 0 \end{bmatrix}$$

and R_{xq} is the rotation matrix which transforms the $[\overline{x}, \dot{\overline{x}}]$ coordinates to [q, q] coordinates. Explicit expressions for R_{xq} and the partials with respect to the elements can be found in W. Kaula, "Theory of Satellite Geodesy," 1966, pp. 67-68.

COMMON Blocks Used:

DC
XYZOUT
CONST1

Variables not in COMMON·

FORTRAN Name	Format	Description
CSI	D	Cos I
SSI	D	Sin I
SA	D	a
SN	D	n, mean motion
OME2	D	$(1 - e^2)$
SE	D	e
SCOMEG	D	Sin Ω
CCOMEG	D	Cos Ω
SOMEG	D	Sin ω
COMEG	D	Cos ω
B(I, J, 1)	D	$\frac{\partial (x, y, z, \dot{x}, \dot{y}, \dot{z})}{\partial (a, e, i, \Omega, \omega, M)}$

RESUME

Purpose. To write a summary of the integration statistics.

Called by

MAIN
ORBIT

Method:

The routine computes the integration statistics by accumulating the desired variables within the subprograms where these variables are being determined and passes the accumulated values thru COMMON/TIMER/.

The variable step statistics are computed by allowing a possibility of 10 step-size ranges of (0 - .4, .4 - .8, .8 - 1.6 min., etc.) and accumulating in each particular range the amount of orbit time spent, and the number of stepsizes taken within that range. The average stepsize is then computed by adding all the stepsizes of a particular range and dividing by the total number of step-sizes in that range. The percent of orbit time is computed by adding the orbit time accumulated and dividing by the total run time. The time that the program spends in setting up the initial starting table is not added into the stepsize analysis statistics.

The routine has 3 entries;

(1) initialize phase for accumulation purposes
(2) accumulation of stepsize statistics
(3) final computation and output of statistical summary.

Calling Sequence:

CALL RESUME (IND)

COMMON Blocks Used:

TIMER	WORKER
LIMITS	COFIT
SSTEP	IORBIT
COWS	

Variables not in COMMON:

FORTRAN Name	Format	Description
IND	I	Entry point indicator
STEPN	R	Old stepsize when a stepsize change occurs (sec.)
STIMES	R	Last time at which a stepsize change occurred (sec.)
IRANGE(11)	I	Number of stepsizes within a particular range
STEP (11)	R	Accumulation of stepsizes within a particular range (min.)
TIME[1] (11)	R	Accumulation of orbit time within a particular range (sec.)
STEP	R	Old stepsize when a stepsize change occurs (min.)

FORTRAN Name	Format	Description
ST1	R	Orbit time spent at a particular step-size range
AVITER	R	Average number of predictor-corrector iterations during a run
DAYEND	D	Total run time in seconds
TIMES	R	Percentage of the total orbit time spent in a particular stepsize range.

WRITER

Purpose. To write the values of the satellite position and velocity vectors and optionally do the following:

(1) write the osculating Keplerian elements
(2) write the partials of position and velocity with respect to parameters being estimated
(3) compute and write the partials of the osculating Keplerian elements with respect to parameters being estimated.

Called By:

MAIN

Calls:

TRANS
ELEMK
APART

Method:

If the drag model is being used in the acceleration computations, the norm of the drag vector is automatically computed The norm is taken to be the largest component of the drag vector.

If the 2-body motion option is being used, the norm of the error vectors is computed automatically. The analytic solution at the requested time is computed and subtracted from the position and velocity vectors computed from the integration; the norm is taken to be the largest component of this vector.

The partials of the osculating Keplerian elements with respect to parameters, if requested, is computed by multiplying the Jacobian

$$\frac{\partial\,(a,\ e,\ i,\ \Omega,\ \omega,\ M)}{\partial\,(x,\ y,\ z,\ x,\ \dot{y},\ z)}$$

by the matrix

$$\frac{\partial\,(x,\ y,\ z,\ x,\ \dot{y},\ z)}{\partial\,(x_0,\ y_0,\ z_0,\ x_0,\ y_0,\ \dot{z}_0,\ C_{nm},\ S_{nm},\ \ldots)}$$

Calling Sequence:

CALL WRITER (PXPX0)

COMMON Blocks Used·

WORKER	XYZ	XYZOUT
LIMITS	NON3	CONST2
DRGBLK	COWS	DC
IORBIT	TIMER	
COFIT		

Variables not in COMMON:

FORTRAN Name	Format	Description
TREQ	D	Request time (time from epoch in seconds)
CON	D	Cross product magnitude of position and velocity vectors
DROG(3)	D	Component of drag vector
DN	D	Norm of drag vector
TI	D	Request time (time from epoch in secs.)
TX(3)	D	Analytic 2-body value of position vector
TXD(3)	D	Analytic 2-body value of velocity vector
EV	D	Norm of error vector for position
EVD	D	Norm of error vector for velocity

7.5 ORBGEN COMMON Block Variable Description

The following section contains the COMMON block descriptions of the new COMMON areas used in the ORGBEN program.

/OPT/

COMMON/OPT/OSTEP

Variable Name	Format	Description	Program Where Defined	Program Where Used
OSTEP	D	Optimum stepsize	TEST	MSTART

/TIMER/

COMMON/TIMER/TOTIME, TABLET(2), CTIME(2), STIMED, STEPD, NOFT(2), NOFC(2), NOCOWL(2), ITERS, ITERMS(2), NOSTEP(2)

Variable Name	Format	Description	Program Where Defined	Program Where Used
TOTIME	R	Total run time	MAIN	ORBIT OSTEP
TABLET (2)	R	TABLET(1) - Time spent in TABLE for equations of motion TABLET(2) - Time spent in TABLE for variational equations	MSTART	RESUME
CTIME (2)	R	CTIME (1) - Time spent in CSTEP for equations of motion CTIME(2) - Time spent in CSTEP for variational equations	CSTEP	RESUME
STIMED	R	Time spent at a particular stepsize	TEST	RESUME
STEPD	R	Old stepsize	TEST	RESUME
NOFT(2)	I	NOFT(1) - Number of times FRCS routine called by equations of motion when computing starting table NOFT(2) - Number of times VEVAL routine called by variational equations when computing starting table	FRCS VEVAL	RESUME
NOFC(2)	I	NOFC (1) - Number of times FRCS routine called by CSTEP NOFC (2) - Number of times VEVAL routine called by CSTEP	FRCS VEVAL	RESUME

/TIMER/(continued)

Variable Name	Format	Description	Program Where Defined	Program Where Used
NOCOWL (2)	I	NOWCOWL(1) - Number of Cowell steps for equations of motion NOCOWL(2) - Number of Cowell steps for variational equations	CSTEP	RESUME
ITERS	I	Total number of predictor-corrector iterations for equations of motion in CSTEP	CSTEP	RESUME
ITERMS (2)	I	ITERMS(1) - Total number of corrector iterations for equations of motion when computing table of ITERMS(2) - Total number of corrector iterations for variational equations when computing starting table	MSTART	RESUME
NOSTEP (2)	I	NOSTEP(1) - Total number of step changes when computing starting table NOSTEP(2) - Total number of step changes when in CSTEP	TEST	RESUME WRITER

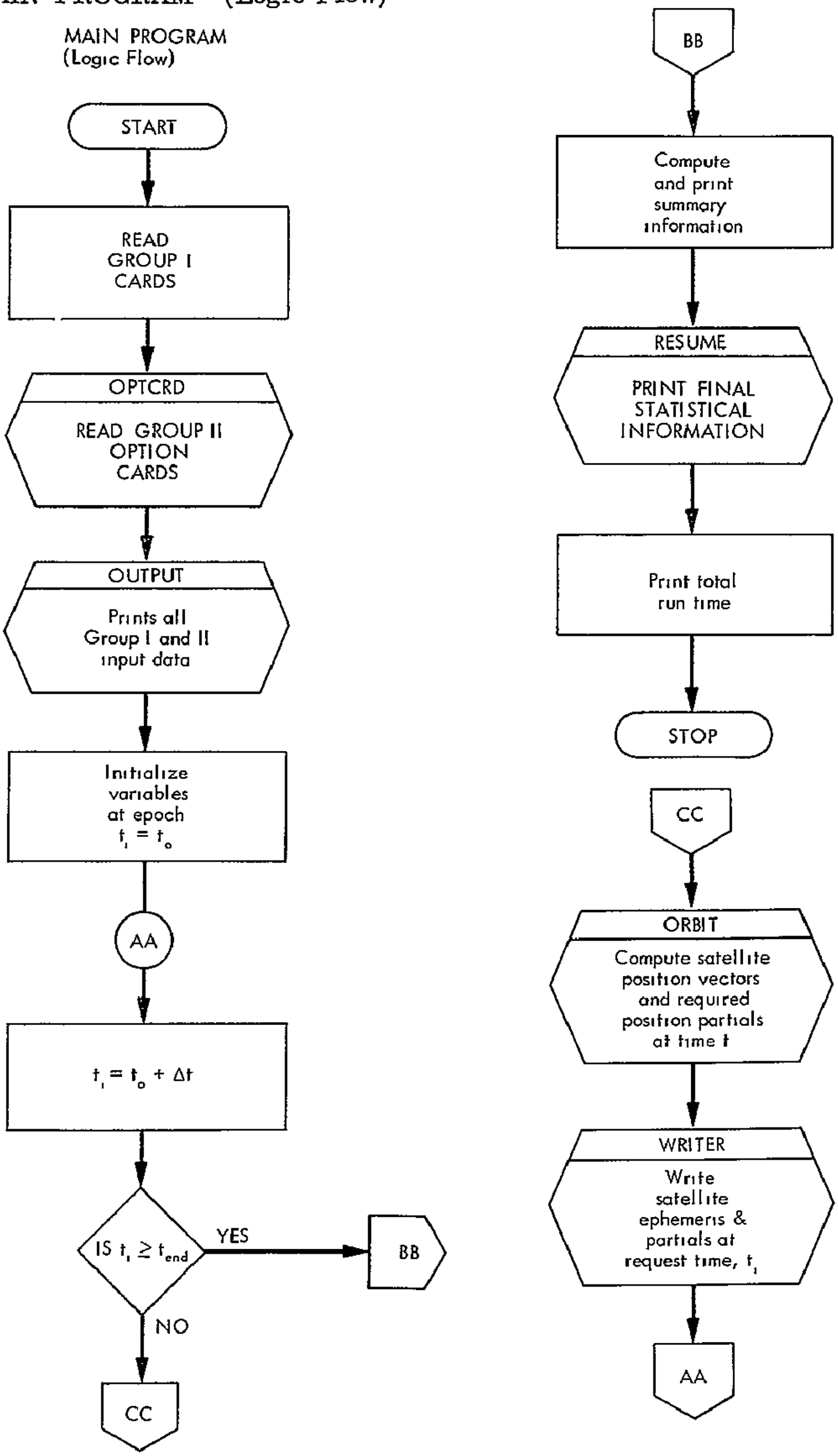
7.6 ORBGEN Flow Charts and Subroutine Summaires

The following section contains the flow diagrams of the MAIN or control programs in ORBGEN, as well as a summary of new modules used in the programs.

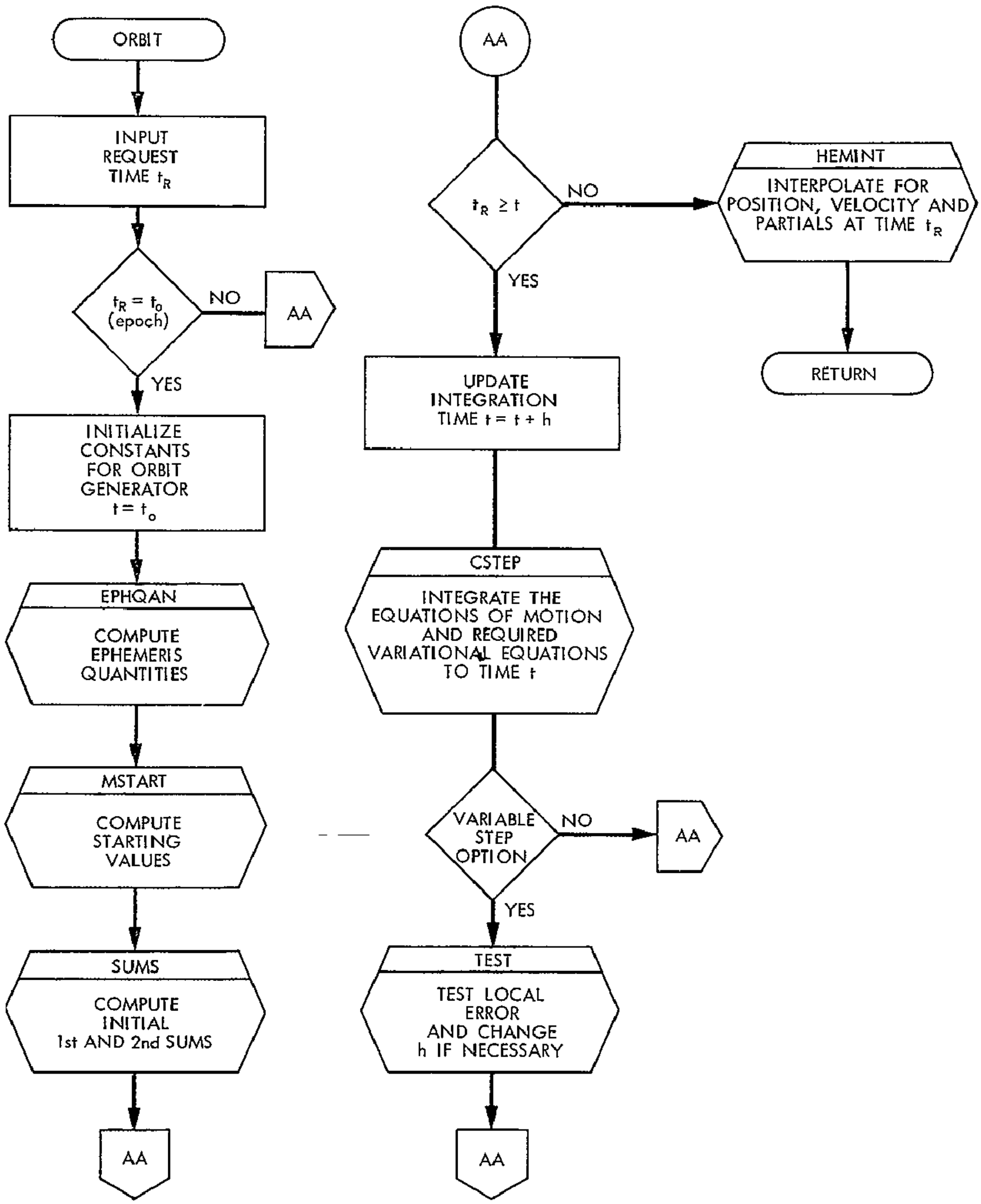
MAIN:

Controls the integration of an orbit for a particular time span to generate a satellite ephemeris at equally spaced intervals. In addition, optionally, position partials can be generated along with the satellite ephemeris.

MAIN PROGRAM (Logic Flow)



ORBIT SUBROUTINE



Subroutine Summary

APART — To compute the Jacobian of the osculating Keplerian elements with respect to rectangular coordinates

RESUME — Writes a summary of the integration statistics for those equations being integrated. Some of those statistics are: average number of predictor-corrector iterations, total number of Cowell steps, number of stepsizes selected within a particular stepsize range and the total amount of orbit time spent in a particular stepsize range.

WRITER — Writes the values of the satellite position and velocity vectors and optionally the partials of position and velocity with respect to selected parameters at the requested time. In addition, if osculating Keplerian elements are requested, then the osculating Keplerian element partials with respect to selected parameters will be written at the required time.

References

1. Velez, C. E. and Brodsky, G. P., "GEOSTAR-I, A Geopotential and Station Position Recovery System," NASA X-Document X-553-69-544, Nov. 1969.

2. Peabody, P. R., "General System Design for DODS," CSC report no. ND-9758-104-2-1, Aug. 1967.

3. Velez, C. E. and Maury, J. L., "Deviation of Newtonian Type Integration Coefficients and Some Applications to Orbit Calculations," NASA TND-5958, Dec. 1969.

4. Finely, G., "GEOSTAR-M SYSTEM (Multi-Arc), OPERATING GUIDE GEOSTAR-I, II, III, OGLA, MERGE, AND SOLVE," Prepared by IBM Corp., under NASA Contract No. NAS 5-00022, April 1970.

APPENDIX A1

ORBGEN INPUT CARD FORMAT DESCRIPTION

Data Cards

The data cards used to define a case are divided into two logical groups:

Group 1 - Cards which must be present to define each run. There are 7 of these cards which must appear in a fixed order at the beginning of the data deck. They provide labels and the orbital elements.

Group 2 - Option cards; these cards provide options to the user such as desired print interval, selection of outputs and position partials. The ORBIT and OUTPUT cards are necessary to define an orbit generator run. The Group 2 cards are placed after the Group 1 cards and may appear in any order.

A detailed description of the card formats for each group follows. Table 2 defines the format specification codes used for individual cards. The last card in any deck must be a standard card ending a data set (/* in columns 1 and 2).

Table 2. Format Specification Interpretation

Key: n, m = integer numbers

b = a blank space

Format Code	Interpretation
In	digits with no decimal point right adjusted in a field of n columns example: 25 in an I3 format: b25
Fn, m	digits with a decimal point anywhere in a field of n columns <u>or</u> digits punched with no decimal point, in which case the point will be assumed between the m-1th and mth column of the field example: 30.1 in an F5.2 format: b30.1 or 30.1b or b301b
Dn, m	digits with a decimal point anywhere in a field of n columns <u>or</u> digits right justified in a field of n columns with an exponent of the form D±XX, where XX is the power of 10 to which to raise the number. If there is no decimal point it will be assumed to be m places to the left of the "D". example: 30.1 in a D8.5 format: b30.1bbb or 30.1D+00 or 301.D-01, etc.
An	n alphanumeric characters
En, m	digits with a decimal point anywhere in a field of n columns <u>or</u> digits right justified in a field of no columns with an exponent of the form E±XX, where XX is the power of 10 to which to raise the number. If there is no decimal point it will be assumed to be m places to the left of the "E". example: 30.1 in a E8.5 format: b30.1bbb or 30.1E+00 or 301.E-01, etc.

TITLE INFORMATION
CARDS 1, 2, 3

Columns	Format	Description
1–72	12A6	Identification to be printed on all output generated by the case

REFERENCE DATE
CARD 4

Columns	Format	Description
1-6	I6	Reference date of the epoch elements year, month, day (YYMMDD)

EPOCH DATE
CARD 5

Columns	Format	Description
1-6	I6	Year, Month, Day (YYMMDD) - Epoch date*
7-10	I4	Hour, minute (HHMM)
11-17	D7.4	Seconds (SS.SSSS)
24-30	I3	Satellite ID, 5-7 digit identification number.
73-80	A8	Satellite name to be printed in this run.

*NOTE: The epoch time must be before the start time.
EPOCH = date of initial position and velocity vector.

POSITION VECTOR
CARD 6

Columns	Format	Description	
1-24	D24.16	The X component	Initial position vector in meters
25-48	D24.16	The Y component	
49-72	D24.16	The Z component	

or

Columns	Format	Description	
1-24	D24.16	Semi-major axis (meters)	Keplerian elements
25-48	D24.16	Eccentricity	
49-72	D24.16	Inclination (degrees)	

Note: If the absolute value of the 2nd element on this card is less than 1.0, the elements on cards 3A and 3B are assumed to be Keplerian elements.

VELOCITY VECTOR
CARD 7

Columns	Format	Description	
1-24	D24.16	The $\dot{X}$ component	Initial velocity vector meters/second
25-48	D24.16	The Y component	
49-72	D24.16	The Z component	

or

Columns	Format	Description	
1-24	D24.16	Right ascension of ascending node (degrees)	Keplerian elements
25-48	D24.16	Argument of perigee (degrees)	
49-72	D24.16	Mean anomaly (degrees)	

Group 2 - Option Cards

All of the Group 2 heading cards have the same format, although subdivisions of these headings will have their own formats. Each heading card is identified by a name starting in column 1, which is read under an A6 format. The name is followed by 9 fields.*

Field	Columns	Field Format
1	7	I1
2	8	I1
3	9	I1
4	10	I1
5	11-25	D15.8
6	26-40	D15.8
7	41-55	D15.8
8	56-70	D15.8
9	71-80	D10.8

*Note: Fields 5 thru 9 of the heading cards are read under a decimal format and MUST CONTAIN A DECIMAL POINT

A detailed description of each option card, in alphabetical order, follows.

COEFG CARD GROUP
Header Card

Name	Columns	Format	Description
COEFGP	1-6	A6	This card signifies that geopotential cards are to follow in the input stream. The values of the geopotential coefficients can be changed (prestored values are in BLOCK DATA) and/or position partials can be computed with respect to the geopotential coefficients requested.
	7	I1	6 = compute position partials for state 0 = do not compute position partials for state
	26-40	D15.8	When not zero, partials are computed and printed at each ephemeris point.*

*Position partials are printed unless Keplerian elements are requested at each ephemeris point (see OUTPUT option card), in this case partials of the osculating Keplerian are printed.

COEFGP CARD GROUP
EST and CHG Cards

Name	Columns	Format	Description
EST	1-3	A3	Indicates a required position partial with respect to the parameter on the card.*
	4	I1	0 = use the stored value 1 = use the value on the card
CHG	1-3	A3	Indicates a change in the prestored value for the parameter listed on the card, but no position partial will be computed
	6	A1	Identifies this entry as a C or S parameter

*Note: Either EST or CHG options may be used, but column 4 will only be utilized with an EST entry.

	7-8	I2	Subscript N for parameter
	9-10	I2	Subscript M for parameter
	11-25	E15.8	*Value for the parameter

*Note: E formats must be right adjusted in last 4 columns of the field.

COEFGP Card Group
END Card

Name	Columns	Format	Description
END	1-3	A3	Group end card which must be present when a COEFGP card is used, and placed directly behind array EST or CHG cards.

CTOL1

Name	Columns	Format	Description
CTOL1	1-5	A6	Redefines the predictor-corrector convergence criterion of the integration, CTOL
	11-25	D15.8	CTOL value; default value is 0.5D-05 meters

Normally the user would not use this card and thus would permit the default value to hold. If an error message occurs indicating failure to converge in the predictor-corrector cycle of the integrator, a decrease in stepsize using the STEP1 card is suggested as a corrective measure rather than a change of the CTOL value.

DRAG

Name	Columns	Format	Description
DRAG	1-4	A6	This card redefines the atmospheric drag coefficient.
	11-25	D15.8	C_D - satellite drag coefficient.
	26-40	D15.8	Zero indication no position partials with respect to C_D required.
			Drag perturbations will not be applied if $C_D = 0$.

Note: See Appendix A2 for program determination of drag.

EARTH

Name	Columns	Format	Description
EARTH	1-5	A6	This card redefines the Earth's reference spheroid. The following 2 fields provide redefinition of the limits for the geopotential model to be used, here N and M refer to the subscripts $C_{n,m}$ and $S_{n,m}$.
	7-8	2I1	N+1, highest order to use (initialized to 16)
	9-10	2I1	M+1, highest degree to use (initialized to 16)
	11-25	D15.8	GM - Universal gravitational constant times mass of earth (meter /second)
	25-40	D15.8	A_e - Semi-major axis of Earth's reference speroid (meters)
	41-55	D15.8	f - Inverse of flattening of Earth's reference (meters) Default values GM = 3.9560032 D+14 A_e = 6378165. F = 298 252 These constants are available in COMMON/CONST/as the variables GM1, AE1, and FINV1.
*	56-70	D15.8	= 1., the standard geopotential model is replaced by a 2-body model in the integration of the equations of motion (state) and the integration of state partials. Other forces may be included.
*	71-80	D10.8	= 1., only a 2-body model is used in the integration of the equations of motion for state and the integration for state partials. No other forces are included.

*These options override any force model specifications in the partials integration defined by the PARTS card.

MODE

Name	Columns	Format	Description
MODE	1-4	A6	This card is used to override the program determined used of the variable step or fixed step mode.
	7	I1	= 2, use variable step = 4, use fixed step This sets the internal variable, MODE1.

Note: See Appendix A2 for program determination of mode and stepsize.

MOON

Name	Columns	Format	Description
MOON	1-4	A6	This card redefines the ratio of the mass of the Moon to the mass of the Earth
	11-25	D15.8	Value of ratio of mass of Moon to mass of Earth. If value is zero lunar gravitational perturbations will not be applied Initially the mass ratio is defined to be 0.0122999 in BLOCK DATA. This information is available in block COMMON/ CONST/ as the variable MMOONI.

ORBIT

Name	Columns	Format	Description	
ORBIT	1-5	A6	This card defines the time span of the orbit requested. This card must be present in the data deck.	
	11-25	D15.8	Year, month, day (YYMMDD.) Hour, minute second (HHMMSS.)	start print time
	41-25 56-70	D15.8 D15.8	Yera, month, day (YYMMDD.) Hour, minute, second (HHMMSS.)	end print time

Note The time interval at which to output the satellite ephemeris is specified on the OUTPUT card

ORDER1

Name	Columns	Format	Description
ORDER1	1-6	A6	Redefines the order, ORDER(1), for the integration of the equations of motion
	1 7-8	I2	ORDER(1), default value is 11 Maximum = 12 Minimum = 4

ORDER2

Name	Columns	Format	Description
ORDER2	1-6	A6	Redefines the order, ORDER(2), for the integration of the variational equations for partials of state, drag, solar radiation and the geopotential coefficients
	7-8	I2	ORDER(2), default value is 7 Maximum = 12 Minimum = 4

OUTPUT

Name	Columns	Format	Description
OUTPUT	1-6	A6	This card specifies the output time interval. This card must be present in data deck.
	7	I1	= 1 indicates that rectangular coordinate ground track is requested = 2 indicates that ground track, Keplerian elements and/or partials of the osculating Keplerian elements are requested (see COEFGP option card) = 3 indicates that output times are to be converted from UTC to A1 time.
	10	I1	= 1 indicates list all non-zero gravity coefficients used in the geopotential model
	11-25	D15.8	A value greater than zero in this field specifies that the ground track is referenced to a fixed time frame defined by the REFERENCE card.

PARTS

Name	Columns	Format	Description
PARTS	1-5	A6	This card redefines the force model to be used for the integration of the variational equations. It does not effect the force model used for integrating the equations of motion. The following options denote exceptions to the equations of motion force model for integration of the variational equations.
	11-25	D15.8	= 1., Exclude the standard geopotential model
	26-40	D15.8	= 1., Exclude drag perturbations
	41-55	D15.8	= 1., Exclude solar radiation preturbations
	56-70	D15.8	= 1., Exclude Sun perturbations
	71-80	D15 8	= 1., Exclude Moon perturbations

SAT

Name	Columns	Format	Description
SAT	1-3	A6	This card redefines satellite area and mass.
	11-25	D15.8	Cross sectional area of satellite (meter ^{2})
	26-40	D15.8	Mass of satellite (kilograms)
			Initially the satellite area and mass are define as 0 in BLOCK DATA. This information is available in block COMMON/CONST/ as the variables ASATI and MSATI.
			Drag and solar radiation pressure perturbations will not be applied if either the satellite area or mass is equal to zero.

SOLRAD

Name	Columns	Format	Description
SOLRAD	1-6	A6	This card redefines the satellite reflectivity
	11-25	D15.8	S_R = Satellite reflectivity (default = 1.5)
	26-40	D15.8	Zero indicates no position partials with respect to S_R are required.
			Solar radiation pressure perturbations will not be applied if S_R = 0.

STEP1

Name	Columns	Format	Description
STEP1	1-5	A6	Redefines the stepsize value, CDEL(1), to be used for integrating the equations of motio
	11-25	D15.8	CDEL(1) = stepsize (secs). Default value is 100. seconds.

STEP2

Name	Columns	Format	Description
STEP2	1-5	A6	Redefines the stepsize value, CDEL(2), to be used for integrating the variational equations.
	11-25	D15.8	CDEL(2) = stepsize (secs.), Default value is 100. seconds.

STOLI

Name	Columns	Format	Description
STOLI	1-4	A6	Redefines the predictor-corrector convergence criterion of the multistep starting process.
	11–25	D15.8	STOLI value (default 1.0×10^{-13})
	26–40	D15.8	Total number of corrector iterations allowed in the multistep starter (default = 15).

Name	Columns	Format	Description
SUN	1-3	A6	This card redefines the ratio of the mass of the Sun to the mass of the Earth.
	11-25	D15.8	Value of ratio of mass ratio If value is zero, solar gravitational perturbations[1] will not be applied.
			Initally the mass ratio is defined as 332951.3 in BLOCK DATA. This information is available in block COMMON/ CONST/as the variable MSUNI.

TOLS

Name	Columns	Format	Description
TOL	1-3	A6	Redefines the upper and lower bounds on truncation error for step size modification
	11-25	D15.8	TOL1 or T_1, the upper bound, default value is .25 D-4 meters
	26-40	D15.8	TOL2 or T_2, the lower bound, default value is .25 D-10 meters
	41-56	D15.8	TOL3 or R, a nominal value for the local truncation error, default value is .25 D-7 meters.
	56-70	D15.8	STEPMIN, the minimum stepsize in seconds, default value is 5 seconds.

Note: These tolerances must satisfy $T_1 \leq R \leq T$.

APPENDIX A2
ORBGEN PROGRAM DEFINITIONS AND SAMPLE RUN DECK

Internal Program Definition of Drag Coefficient and Stepsize Option

ORGBEN provides internally programmed default values and options for drag coefficient and stepsize when certain orbital conditions occur.

Drag Coefficient

C_D, the drag coefficient is initialized and position partials will be computed for a perigee height less than 800 km. In such a case·

$$C_D = 2\ 3$$

$$\text{stepsize} = 75 \text{ seconds}$$

The input DRAG card may be used to override this option.

Stepsize

The nominal stepsize in the fixed step mode is 100 seconds. However, for eccentricity less than .01 and perigee height greater than 1500 km., the stepsize is computed as:

stepsize = perigee height * 8.849557E-3 + 86.72566

stepsize maximum = 400 seconds

The variable step option is selected for orbits with eccentricity greater than .02. In such a case, the initial stepsize is 24 seconds.

The STEP1, STEP2 and MODE cards of ORBGEN may override these options.

SAMPLE RUN DECK SETUP

```
//STEP4  EXEC  LINKGO, REGION, GO = 400K
//LINK.SYSLKM DD DSNAME=**** SYSTEM TAPE ****
//LINK.OBJECT DD *
ENTRY MAIN
/*
//GO.FT35F001DD UNIT = DISK, DCR = (RECFM = VBS,LRECL = 44, BLK
  SIZE = 4404),
//             SPACE = (CYL, (10,1))
//GO.DUM  DD  DSNAME = *.LINK.SYSLMOD, DISP = (OLD,DELETE)

//GO.DATA5  DD *
  ORBIT GENERATOR RUN WITH **** CHANGES IN THE STANDARD FORCE
                                MODEL AND OUTPUTTING THE PRE-
                                DICTED EPHEMERIS EVERY 60 SECS.

651120
651126012736.0000 1      65891
 532242.523916446        6357536.01341798      5275907.36107666
  -4803.1367878774       -3236.3075474982       3657.0878411886
SAT         1.23          172.5          651129        000500.
ORBIT 40  651128.      235500.           651129        000500.
SOLRAD  1.5
OUTPUT1   60.
STEP1     100.
COEFGP6
CHG  C0303     1.564  E-07
CHG  C1513     0.0    E+00
CHG  S1513     0.0    E+00
CHG  C1713     0.0    E+00
CHG  S1713     0.0    E+00
END
EARTH 18183.986009000D+14 6378142.          298.255
/*
//
```


lll